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PREDICTION OF GEOLOGIC AND HYDROLOGIC CONDITIONS AHEAD OF RAPID EXCAVATION OPERATIONS BY INHOLE GEOPHYSICAL TECHNIQUES

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Bureau of Mines

Prepared for:

Advanced Research Projects Agency

November 1973

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

DENVER MINING RESEARCH CENTER
DENVER, COLORADO

FINAL TECHNICAL REPORT

Bureau of Mines In-House Research

Prediction of Geologic and Hydrologic Conditions
Ahead of Rapid Excavation Operations
by Inhole Geophysical Techniques

Sponsored by

Advanced Research Projects Agency (ARPA)
ARPA Order No. 1579, Amendment No. 3
Program Code No. 2F10

Form Approved
Budget Bureau No.: 22-R0293

Final Technical Report

ARPA Order No.: 1579 Amendment 3

Effective Date: Jan. 1, 1972

Program Code: 2F10

Expiration Date: June 30, 1973

Originating Agency: USBM, Denver Mining Research Center
Building 20, Denver Federal Center
Denver, CO 80225

Amount Funded: $46,000

Principal Investigator: James H. Scott
Telephone No.: 303/234-2088

Title: Prediction of Geologic and Hydrologic Conditions Ahead of Rapic Excavation Operations by Inhole Geophysical Techniques

Sponsored by:

Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, Virginia 22209

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ILLUSTRATIONS

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
P-87-4

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Prediction of Geologic and Hydrologic Conditions Ahead of Rapid Excavation Operations by Inhole Geophysical Techniques

5. TYPE OF REPORT & PERIOD COVERED
Final Technical Report
Jan. 1, 1972 - June 30, 1973

6. PERFORMING ORG. REPORT NUMBER
P-87-4

7. AUTHOR(s)
James H. Scott and Joe Sena

8. CONTRACT OR GRANT NUMBER(s)
—

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Bureau of Mines, Denver Mining Research Center
Building 20, Denver Federal Center
Denver, Colorado 80225

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
ARPA Order No. 1579, Amend.3, Code Number 2F10

11. CONTROLLING OFFICE NAME AND ADDRESS
Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, Virginia 22209

12. REPORT DATE
November 1973

13. NUMBER OF PAGES
33

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
U.S. Bureau of Mines
Twin Cities Mining Research Center
P.O. Box 1660
Twin Cities, Minnesota 55111

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Distribution of this document is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Geologic Prediction
Rapid Excavation
Delineation Systems
Geophysical Methods
Detection
Evaluation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DD Form 1473: Report Documentation Page

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The inhole geophysical measurement system was developed and performance tests were completed. Computer techniques were developed for analyzing and plotting all logging data. Calibration models were designed, constructed and laboratory tests were completed to determine the physical characteristics of the models with accuracy.

Accomplishments of special significance include the following: (1) the successful temperature stabilization of the magnetic susceptibility borehole measurement equipment, (2) implementation of a truck-mounted high-speed digital tape recording system capable of real-time field recording of acoustic waveforms digitized at intervals as small as 0.5 microseconds, (3) development of a unique computer method for detecting the arrivals of P- and S-waves by cross-correlation of acoustic waveforms, and (4) the development of computer techniques for synthesizing and plotting logs of Poisson's ratio, elastic moduli (Young's, shear and bulk), location and orientation of fractures, and RQD.

PREDICTION OF GEOLOGIC AND HYDROLOGIC CONDITIONS AHEAD OF RAPID EXCAVATION OPERATIONS BY INHOLE GEOPHYSICAL TECHNIQUES

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PREDICTION OF GEOLOGIC AND HYDROLOGIC CONDITIONS AHEAD OF RAPID EXCAVATION OPERATIONS BY INHOLE GEOPHYSICAL TECHNIQUES

by

James H. Scott and Joe Sena

INTRODUCTION

It is generally recognized that effective planning for deep tunneling by rapid excavation techniques requires detailed and accurate knowledge of the specific physical characteristics of rock at tunnel depth prior to construction. This research project was directed toward (1) developing new and improved techniques of acquiring this information by inhole geophysical measurements, and (2) developing new computer-aided interpretation techniques for analyzing and displaying the measurement data.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical assistance of William J. Larson in developing the geophysical logging measurement system and Richard G. Burdick in developing the Fortran programs for plotting the computer-analyzed logs.

DISCUSSION OF THE PROBLEM

Unknown or poorly defined geologic and hydrologic conditions, probably more than any other factors, determine the degree of difficulty and the total cost of excavating and supporting underground openings created by rapid excavation methods. The development of new or improved geological and geophysical methods for accurately characterizing the rock and hydrologic conditions ahead of rapid excavation operations are needed to develop efficient rapid excavation tunneling and mining systems.

ARPA program goals of achieving advance rates of 200 feet/day at depths of several thousand feet in hard rock require that detailed rock properties be obtained by accurate and reliable in-situ measurements made in advance of tunnel construction. Results are needed for optimizing construction by anticipating geologic-hydrologic conditions, especially in problem zones, and adjusting tunneling techniques accordingly.

Geophysical well logging can provide the most accurate and detailed information possible prior to actual tunneling. These measurements can fill the gap between reconnaissance surface geophysical surveys which can be expected to delineate gross geological features, and detailed underground measurements that are being developed to map and define rock properties foot-by-foot. They can provide a final "look" at underground conditions before a commitment is made to follow a certain tunnel route. Inhole measurements offer a means of greatly increasing the amount of information that can be extracted from drill holes which are an expensive investment when depths of several thousand feet are involved.

RESEARCH PLAN

During the first phase of the project, supported by FY 1971 ARPA funding, a mobile geophysical well logging unit was designed and partly developed and calibrated by modifying existing Bureau of Mines geophysical logging equipment. The equipment was modified to operate in small-diameter boreholes drilled in hard-rock environments to depths of 3000 feet. Calibration models were designed and partially constructed, and preliminary computer techniques were developed for analyzing measurement data obtained during Phase I.

The research plan for Phase II, supported by FY 1972 ARPA funding, was to complete the development, testing and calibration of the measurement system, to complete the construction and testing of the calibration models, and to develop computer-aided interpretation techniques for analyzing and displaying measurement data. The completion of Phase II was delayed somewhat by late delivery of electronic subsystems, but otherwise the original plan was followed successfully and without significant change.

GEOPHYSICAL LOGGING MEASUREMENT SYSTEM

The geophysical logging measurement system is housed in a custom-designed van mounted on a 2-ton truck (Figure 1). The van is divided into two compartments. The rear compartment contains the winch, cable draw-works system and boom elevator mechanism, all accessible through the rear doors of the truck (Figure 2). Prior to transit the boom is rotated forward so that the pulley wheel is over the cab, and then it is lowered and fastened down against the top of the van. In operation, the boom is elevated and rotated so that the logging cable passes down through the pulley directly over the hole to be logged as shown in Figure 3. The boom was designed to make it possible for one man to handle probes up to 20 feet long safely and conveniently. In Figure 3, the logging truck operator is shown preparing to change probes prior to the next logging run. When not in use, probes are stored in horizontal tubes just beneath the back doors of the truck where they can be locked in place during transit.

The cable draw-works system in the rear compartment of the truck is shown in Figure 4. The winch is powered by a variable speed 100 vdc 1.5 H.P. reversible motor with a Morse SCR motor control unit. The motor is coupled to the winch through a Lima transmission with 4 mechanically selectable drive speeds and an electric 2-speed clutch. Controls and meters for the winch are located in the forward compartment beneath the long horizontal window in the partition separating the two compartments (Figure 5). The meter on the left is used to monitor load weight on the cable, and is equipped with adjustable underload-overload indicators and switches that turn the winch power off when

FIGURE 1. - Geophysical Logging Truck, Side View, Showing Boom and Pulley System for Handling Long Probes.

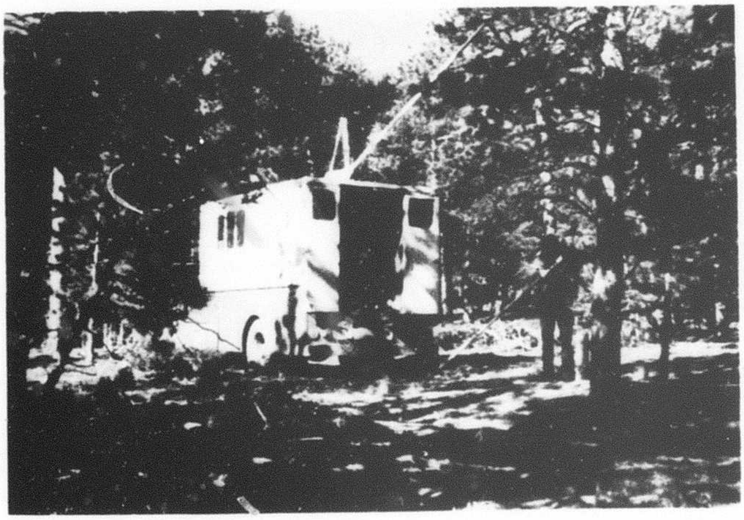

FIGURE 2. - Geophysical Logging Truck, Rear View, Showing Access to Winch Through Open Doors.

FIGURE 3. - Logging Truck Operator Preparing to Change Probes. Note Recessed Probe Storage Rack Beneath Rear Doors of Truck.

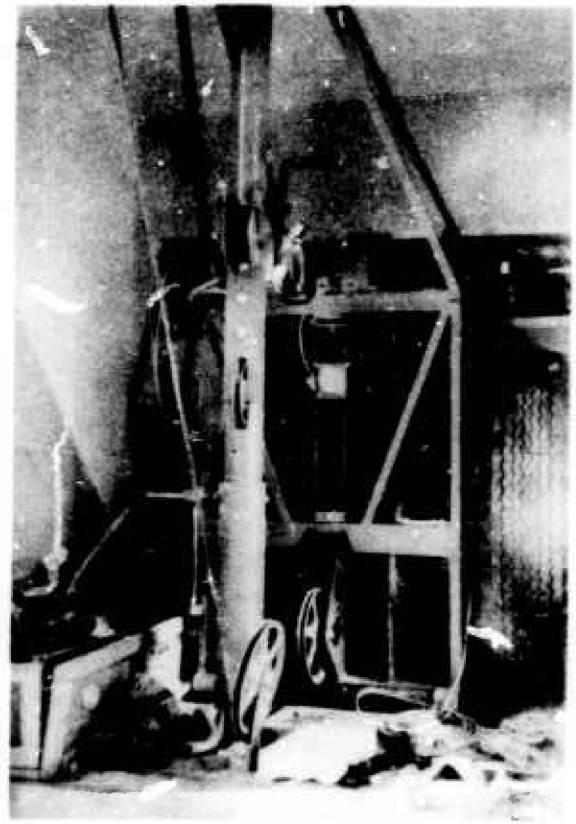

FIGURE 4. - Draw-Works With Winch Drive and Cable Pulley System in Background, Boom Crane Elevator and Supporting Post in Foreground.

preset limits are exceeded. This arrangement prevents cable backlash when the probe is being lowered and is unexpectedly stopped by an obstruction in the hole, and it also prevents over-stressing the logging cable and boom support if the probe hangs up as it is raised up the hole.

In Figure 5 the meter on the right beneath the window is used to monitor cable speed. Push-button switches beneath the meters are used to select low or high speed ranges, to select up or down directions, to stop the winch, and to engage or disengage the clutch. The variable speed control knob is located to the right of the push-button switches. A mechanical footage indicator for backup of the electronic footage counter is located between the two meters above the push-button switches.

To the right of the long horizontal window shown in Figure 5 are meters and switches for monitoring and controlling the 110 vac gasoline-powered motor generator that is installed in a separate compartment located at the lower left-rear of the van. The gasoline motor is vented to the outside through an exhaust pipe that extends above the top of the van to prevent exhaust fumes from accumulating in the van.

The instrumentation modules are located in the forward compartment of the van shown in Figure 6. All of the control modules are *NIM compatible so that they can be unplugged from the NIM bin power supplies in the mobile logging van and plugged into "porta-bins" for use with a portable draw-works and recorder system in remote areas where access by truck is impossible or impractical, or underground in tunnels.

* Nuclear Instrument Module, AEC Spec. TID-20893.

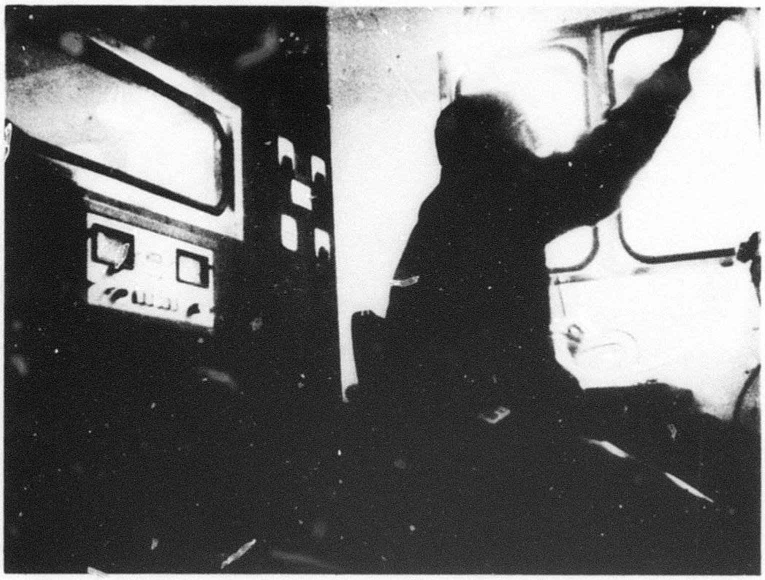

FIGURE 5. - Meters and Controls for Cable Draw-Works System Located Beneath the Window Behind the Operator in the Forward Compartment.

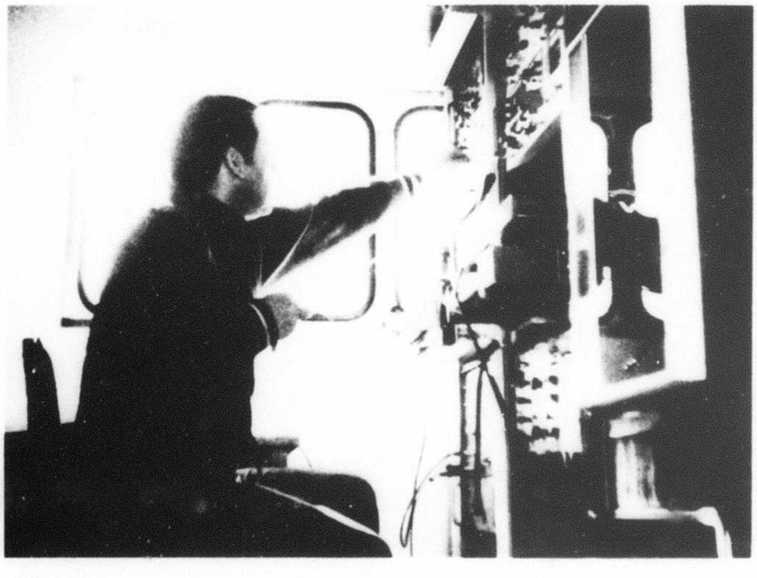

FIGURE 6. - Measurement Control Modules Located in Front of Operator in the Forward Compartment.

Referring to Figure 6, and to the instrument rack near the windows, the modules in the upper left bin are the nuclear pulse detection and calibration modules including the ratemeter, pulse generator, timer-scaler, and output printer.

In Figure 6 the operator is plugging a connecting cable into the cable patch panel just below the nuclear modules. This panel also contains meters for monitoring voltage and frequency of ac power. Below the patch panel is the downhole dc power supply which provides adjustable regulated dc power to the probes. Beneath the downhole power supply is the 3-pen chart recorder for making paper records of logging measurements. Directly beneath the chart recorder and also to the right of the recorder are the electric logging panels and modules.

Referring to the middle rack in Figure 6, above the electric logging module is an X-Y recorder mounted on the pull-out shelf (out of view) is the high-speed digitizer for sampling and buffering acoustic waveform data. Above the digitizer is an oscilloscope for testing and debugging the equipment and for displaying acoustic waveforms. Above the scope and at the top of the middle rack are modules for control and operation of the caliper probe, 3-point resistance probe, and magnetic susceptibility probe.

Referring to the rack on the right in Figure 6, the large rectangular cabinet with glass door contains the digital magnetic tape recorder, and just below it is the digital tape buffer unit. Above the tape recorder and nearly out of view is the digital interface unit and the electronic depth counter, the output of which is recorded on tape along with a selectable number of channels of geophysical measurement data for which control, sequencing and buffering functions are accomplished by the interface unit.

A unique high-speed data acquisition and buffering system makes it possible to digitize incoming acoustic waveform signals from the three receivers of the acoustic probe and to record them serially, in repeating sequence, on computer-compatible 9-track digital magnetic tape at a density of 800 characters/inch. A digitizing interval of either 2 or 5 microseconds has been found to be adequate for sampling most acoustic waveforms, although an interval as small as 0.5 microsecond can be selected if very fine resolution is needed. Word length is 8 bits, and buffering in the digitizer provides for storing 1024 words per record. In operation, after the 1024 words are formed and stored in the digitizer buffer, they are transferred to the tape buffer where they are held until they can be transferred to the magnetic tape at tape recording speed. After this is accomplished, another 1024 words are formed representing the waveform picked up from the next receiver in sequence, and the process is repeated. In this manner, 1024-word records in sets of three, one for each receiver on the probe, are obtained at one-foot intervals in the borehole at logging speeds of 30-40 feet/minute, or at half-foot intervals at speeds of 15-20 feet/minute.

The functional relationships of various modules and system components are shown in the block diagram of Figure 7. The flow of information starts with the borehole probes at the lower left-hand corner of the illustration, and proceeds to the right along lines indicated by arrows. In field operations, measurement information is finally stored on digital magnetic tape (lower right-hand corner of Figure 7). Recorded field data are later analyzed by computer after the tape is brought back or sent back to the laboratory. Graphic recorders in the truck are used to monitor the operation of the data acquisition system, and to provide back-up for the digital magnetic tape recording system. If the magnetic tape recorder in the logging van malfunctions, the graphic records can be digitized by use of a laboratory digitizer-tape recorder system,

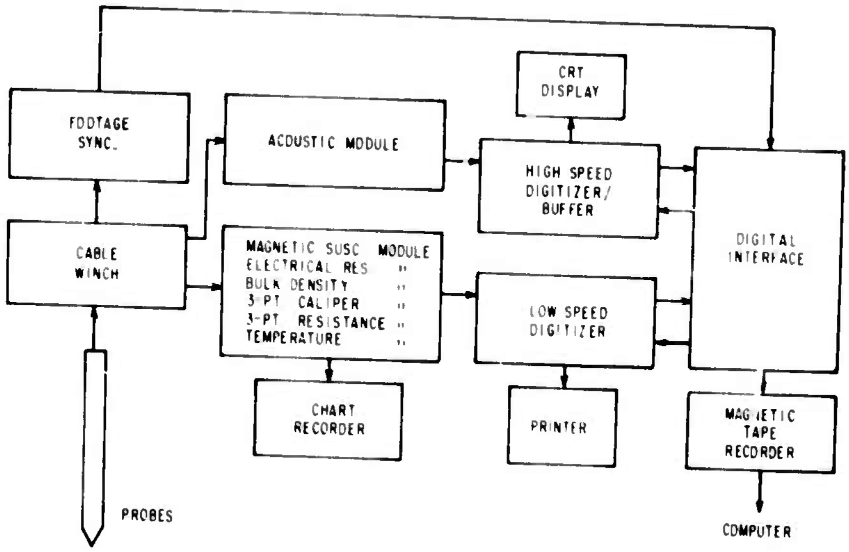

FIGURE 7. - Block Diagram Showing Functional Relationships of Various Components of Geophysical Logging Measurement System.

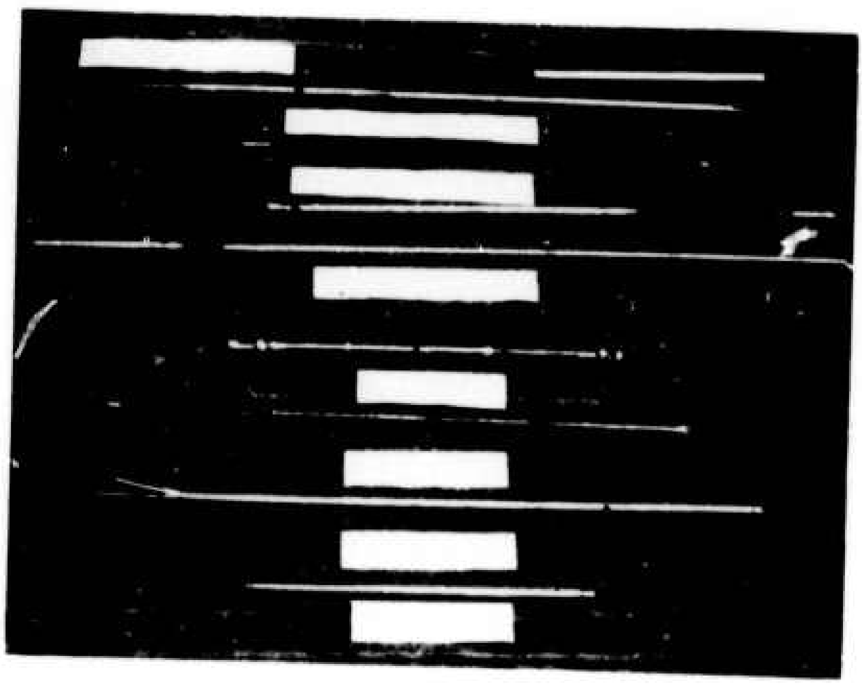

FIGURE 8. - Geophysical Logging Probes. Note Meter Stick in Upper Right-Hand Corner for Scale.

and the tape thus prepared can be used to provide optional input to the computer programs described later in the report.

Logging measurement probes developed or adapted for determining rock character ahead of tunneling are shown in Figure 8. At the top of the illustration is the magnetic susceptibility probe which is sensitive to the volumetric concentration of magnetic minerals in rock. The susceptibility log can be made in boreholes filled with either fluid or air. Because magnetic minerals such as magnetite and ilmenite, which are normally present in low concentration in igneous rocks, are oxidized to non-magnetic minerals in alteration zones, anomalously low levels of magnetic susceptibility in a rock mass are a direct indication of chemical alteration and an indirect indication of zones of faulting and potential water inflow that are commonly associated with mineral alteration. The magnetic susceptibility probe shown in Figure 8 was specially designed to minimize problems of temperature instability which have limited the accuracy of inhole magnetic susceptibility measurements made in the past with equipment described by Broding and others (2). Temperature is stabilized inside the probe by a thermostatically controlled heater element, and sensor components are designed for temperature compensation to minimize the effect of small residual temperature fluctuations.

The next probe down from the top of Figure 8 is the electrical resistivity probe equipped with "normal" electrode spacings of 16 and 64 inches. Resistivity logs can be made only if holes are filled with conducting fluid (water or drilling mud). In the "normal" electrode configuration, one side of the current circuit is connected to an electrode located at the bottom of the logging probe, and the

other side is connected to the armor of the logging cable. A regulated square-wave current source is introduced between these two points. Two simultaneous measurements of electrical resistivity are made at two different sized sample volumes by the use of potential electrodes located at spacings of 16 inches and 64 inches from the current electrode on the probe. Separate measurements are made of the potential between each of the two potential electrodes on the probe and a common surface ground potential electrode. With the square-wave current regulated at a constant value, apparent resistivity is proportional to measured potential, and therefore an analog voltage representing apparent resistivity can be obtained by appropriate electronic scaling of the two potential measurement signals. Resistivity measurements are made at two different electrode spacings to make it possible to take into account the effects of fluid in the borehole, invasion of borehole fluid into porous formations, and to provide different levels of thin bed resolution and sample volume averaging as discussed by Keller and Frischknecht (7). Resistivity logs are useful for distinguishing different rock types because of the sensitivity of the measurement to the volumetric water content of rock and its salinity. In particular, water-saturated clay alteration minerals that occur in fractures have a very low resistivity, commonly in the range of 1-10 ohm-meters, which contrasts markedly with unfractured hard rock which typically has resistivities in the range of 100-1000 ohm-meters.

Just below the electrical resistivity probe in Figure 8 is the acoustic waveform probe. Operation of this probe requires that the borehole be filled with fluid to transmit the acoustic pulse from the probe to wall rock and back. The lower transducer section contains the magnetostrictive pressure pulse transmitter on the left and three pressure-sensitive piezoelectric ceramic receivers on the right. The spacing from the transmitter to the first receiver is 4 feet, and the

three receivers are 1½ feet apart. In operation, the spring sections (above the transducer section in Figure 8) are connected to each end of the transducer section, so that the probe is centralized in the hole. Centralization is needed to keep acoustic waves in phase at the receivers. The center frequency of the acoustic pulse emitted from the transmitter is rather high--approximately 40 kHz--so it is important that acoustic arrivals be kept in phase to prevent the signal from being degraded at the receivers. Acoustic log measurements are useful for determining rock type, degree of fracturing, and for computing Poisson's ratio, and dynamic elastic moduli as discussed by Geyer and Myung (6) and Morris and others (9). These parameters define the elastic properties of rock and are useful for predicting rock mass behavior in response to varying stress conditions caused by tunnel construction.

Below the acoustic probe in Figure 8 is the bulk density probe. The bow spring attached to the probe is used to press the collimated gamma-ray source and detector against the borehole wall to minimize variations caused by changes in hole diameter, borehole rugosity, and variations in the density of the borehole-filling medium (air, water or drilling mud). The gamma-ray source used in the probe is 125 mCi of Cesium-137 in a sealed capsule easily removed from the probe when it is not in use. The gamma-ray detector is a NaI-Tl scintillation crystal (½ inch diameter by 2 inches long) optically coupled to a photomultiplier tube. Spacing between source and detector is adjustable from 9 to 16 inches. Principles of density logging by the gamma-gamma method are described by Tittman and Wahl (11). Density logs may be made in holes filled with either fluid or air. The density measurement is used to distinguish rock

types from one another and to provide numerical values of density needed for computation of elastic moduli.

Below the density probe in Figure 8 is a 3-point caliper probe. The caliper probe can be used in either dry or fluid-filled holes. The arms of the caliper move independently and provide three separate measurements of hole radius at azimuths 120 degrees apart. In operation the probe is connected to a gyroscopically oriented directional probe, and the hybrid unit is centralized in the hole with springs similar to those used with the acoustic probe. Indentations in the hole wall caused by fractures cutting across the hole are detected by the arms of the probes, and the strike and dip of the fractures thus detected can be determined. This is accomplished by measuring the inclination of the hole and the azimuthal orientation of the probe arms at all points along the hole axis with the gyro directional probe. Measurements made with the 3-point caliper probe are obviously useful for detecting fractures and determining their strike and dip, but they are also useful in determining hole diameter which is needed for computing and applying corrections to other logs including electrical resistivity, density and magnetic susceptibility. In addition, hole diameter is useful for distinguishing variations in rock hardness because of the tendency for soft rock to drill out to a larger diameter than hard rock.

Below the 3-point caliper probe in Figure 8 is the 3-point resistance probe. Electrical resistance is measured between the tip of one of the arms of the probe and the other two arm tips connected in common. This resistance measurement is very sensitive to thin fractures perpendicular to the borehole axis, and to thin layers of clay, either in fractures or in bedded rock. The log can also be

used to pick depths to bed or formation contacts with very high precision and resolution. The 3-point resistance probe can be used in either dry or fluid-filled holes.

The probe at the bottom of Figure 8 is a temperature probe which uses a thermistor as a sensing element. This probe is useful for detecting zones of potential water inflow in fluid-filled holes as discussed by Keys and Mac Cary (8) and for estimating environmental temperatures to be encountered during tunnel construction. The probe is usually used in fluid-filled holes, but can be operated in air-filled holes although the measurements are affected adversely by convection of air in the hole.

CALIBRATION MODELS

It is important to provide a means of calibrating geophysical logging equipment if results of computer-aided interpretations are to be meaningful and reliable. Of the various measurement techniques developed in this study, density logging is considered to be the one most prone to error resulting from calibration problems. Therefore, concrete models were carefully designed and constructed with special emphasis on their usefulness for calibrating density probes. The calibration models illustrated in Figure 9 were made with different mixes of concrete so that they would cover the range of density that is normally encountered in borehole logging of various rock types. The low density model was made with light-weight (expanded shale) aggregate and 5 percent air entrainment. The medium density model was made with standard (sand-gravel) aggregate, and the high density model was made with hematite-gravel aggregate. In order to facilitate the determination of empirical hole diameter corrections as part of the calibration procedure, four holes of different diameters (2, 3, 5, and 8 inches) were drilled in the medium-density model. The high and low density models contain only one hole each, 3-inches in diameter, which is typical of the size of exploration holes drilled ahead of tunneling.

Magnetic susceptibility is another borehole measurement requiring careful calibration of equipment because of its sensitivity to temperature drift. Therefore, different amounts of granular magnetite were added to the concrete mixes used in the construction of the three calibration models described above. High-susceptibilities were emphasized in designing the models in order to detect

PHYSICAL PROPERTIES	MODEL 1	MODEL 2	MODEL 3
DENSITY	1.66 g/cc	2.31 g/cc	3.15 g/cc
MAGNETIC SUSCEPTIBILITY	605 μcgs	1685 μcgs	9090 μcgs
VELOCITY	12,600 ft/sec	13,500 ft/sec	12,000 ft/sec
HOLE DIAMETER	3"	8", 5", 3", and 2"	3"

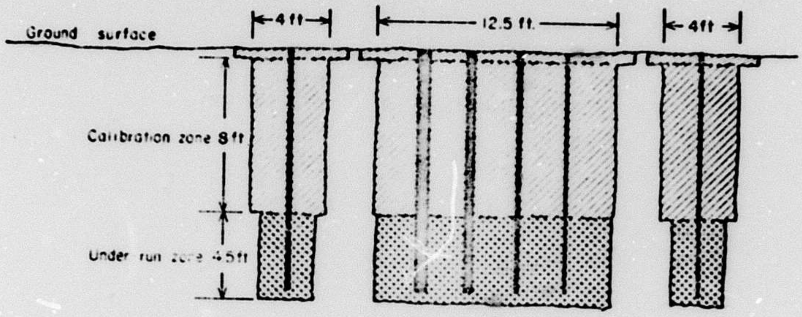

FIGURE 9. - Calibration Models for Geophysical Logging System.

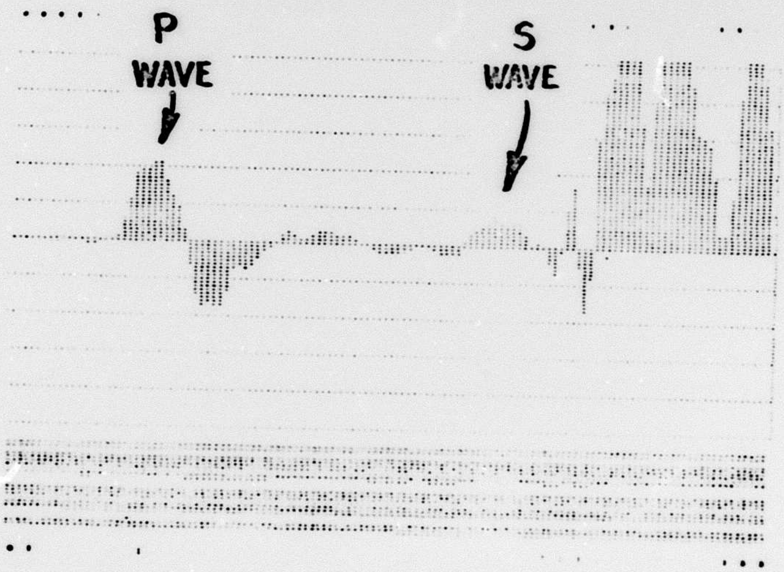

FIGURE 10. - Computer Plot of Cross-Correlation Function Showing Positive Peaks Representing P-Wave and S-Wave Arrivals.

and correct measurement nonlinearities that may occur in the upper part of the susceptibility range.

As a byproduct of the design of the calibration models, variations in the acoustic velocity of the various concrete mixes turned out to be useful for testing and evaluating computer-implemented digital techniques for analyzing acoustic waveform logs.

The models were constructed with an 8-foot calibration zone above a 4.5-foot underrun zone as shown in Figure 9. The underrun zone was provided to accommodate long probes with sensors several feet above the bottom.

The holes in the models are normally filled with water (with anti-freeze added to prevent freezing in wintertime) so that the simulated formations remain water-saturated and density and velocity remain constant. However, the holes may be pumped out temporarily in order to calibrate probes for logging dry holes, or they can be filled with simulated drilling muds of different compositions and different densities to determine empirical corrections for various types of hole fluid.

The logging calibration models are located on government property at the Denver Federal Center where they are available for use by other government agencies and commercial logging companies on a self-serve basis. Information regarding their use can be obtained by contacting the authors of this report.

As an adjunct to the calibration models, a laboratory test tank was designed and constructed to test probes for temperature stability. The tank is equipped with a flow-through hot-cold water system that allows temperature to be varied from 0 to 75 degrees C. The tank is also useful for calibrating the temperature logging probe.

By use of the temperature test tank and the calibration models, it is possible to assure that the density, magnetic susceptibility, acoustic velocity, and temperature logging systems are reliable, stable, and quantitatively accurate before they are taken to remote field sites where such facilities are not available.

COMPUTER-AIDED INTERPRETATION TECHNIQUES

Computers have been used for analysis of geophysical logs by the petroleum industry with methods such as those described by Broding and Poole (1) and the uranium mining industry by use of techniques developed by Scott (10) since the early 1960's. The recent availability of graphic terminals has made it practical to use man-machine interactive techniques for analyzing and interpreting geophysical logs by methods discussed by Gans (5). Computer techniques have also been used to facilitate the derivation and display of synthetic logs, particularly for logs of elastic moduli as presented by Evans and Cotterell (4) and by Geyer and Myung (6).

In the course of implementing computer programs for analyzing logs for predicting geologic and hydrologic conditions ahead of rapid excavation tunneling, many previously developed techniques and ideas were drawn on, and a few new ones were added. The programs were designed for batch computer processing, but with provisions for adapting them to interactive graphic terminal operation in the future as terminals become more readily available.

Perhaps the most significant new computer technique that was developed in this study was a numerical method for determining P- and S-wave velocities from digitized acoustic waveforms obtained with 2-receiver acoustic logging probes (with the transmitter and receivers spaced longitudinally along the probe). The

technique is based on a unique property of the cross-correlation function; its ability to detect and measure the degree of similarity between two waveforms that are compared at a series of progressive time lags. The cross-correlation function is characterized by positive peaks at lag times where alinement of similarities in the waveforms is best, and negative peaks where alignment of similarities is poorest. Therefore, when P-wave or S-wave arrivals detected by the two receivers have similar wave shapes, their alinement is represented by a positive peak on the cross-correlation function at a lag time that corresponds to a specific velocity.

The sensitivity of the cross-correlation technique in this application is improved by limiting computation of the cross-correlation function to segments of waveforms within time windows that exclude irrelevant acoustic energy arriving long before and long after the particular event of interest. The time windows used in this technique are positioned as a function of lag time (which in turn is a function of rock velocity), transmitter-receiver spacings, hole diameter, transducer diameter, borehole fluid velocity, and angle of incidence of ray critically refracted along rock adjacent to the hole. The time windows can be visualized as sliding down the two waveforms as the cross-correlation function is computed at increasing lag times.

The cross correlation function is defined below:

$$C(\tau) = \sum_{j_1}^{j_2} A_j B_{j+\tau}$$

Where $C(\tau)$ = Cross correlation

τ = Lag integer interval (lag time/Δt)

A_j = Amplitude at point j of the digitized wave form obtained by the receiver closest to the transmitter

$B_{j+\tau}$ = Amplitude at the point $j+\tau$ of the digitized waveform obtained by the receiver farthest from the transmitter

$j_1 = \dfrac{TR}{\Delta R/\tau}$ + Delay Interval

$j_2 = j_1$ + Window Interval

Window Interval $\approx 100\ \mu sec/\Delta t$ (Selected by interpreter)

Δt = Digitizing time interval ($\approx 5\ \mu sec$)

TR = Spacing between transmitter and closest receiver

ΔR = Spacing between the two receivers

Delay Interval $= \dfrac{D_h - D_t}{V_f \cos\alpha\, \Delta t}$

D_h = Diameter of borehole

D_t = Diameter of transducers on probe

V_f = Velocity of fluid in borehole

α = Angle of incidence of critically refracted acoustic ray

Computational range of τ: $\dfrac{\Delta R}{V_{max}\Delta t} < \tau < \dfrac{\Delta R}{V_{min}\Delta t}$

V_{max} and V_{min} = maximum and minimum velocities of interest (e.g. 30,000 and 4000 ft/sec)

Figure 10 shows typical results of using the cross-correlation technique to determine P-wave and S-wave velocities. The high amplitude peaks to the right of the S-wave peaks represent direct arrivals of acoustic energy through water surrounding the probe.

Another new technique developed for the computer analysis of geophysical logs in this study is the synthetic construction of an RQD log from analyses of geophysical logs sensitive to fracturing, particularly the 3-point caliper and 3-point resistance logs. RQD is a measure of rock quality defined by Deere and others (3) as the ratio (converted to percent) of the cumulative length if pieces of core with individual lengths greater than some reference length (commonly taken as 4 inches) to the total length of core in a core run.

Some of the display techniques developed for use in this study are also new. To avoid the long turn-around times and relatively high costs associated with pen-and-paper X-Y plotting in batch processing, line printer plotting subroutines were programmed that paralleled the X-Y Calcomp plotting subroutines, and were made available to the user by control card option. Preliminary printer plots of computer-analyzed logs are thus made available to the interpreter so that he can preview the results and make any necessary corrections or revisions before final analysis of log data and subsequent Calcomp plotting is accomplished. Furthermore, the computational and plotting subroutines are organized in such a way as to make them readily adaptable to graphic interactive terminal operation which is even faster and less costly than batch processing and printer plotting.

Three Fortran IV computer programs were developed in this study. The first program, ACOU, is used to compute and display (by printer plot or Calcomp plot) the cross-correlation function used to aid the interpreter in picking P- and S-wave velocities. A flow chart of program ACOU is given in Figure 11.

Velocities determined by use of program ACOU are then submitted by card or tape as input data to the second program, GLIP (Geophysical Log Interpretation Program), along with all other geophysical log data from the same borehole stored on magnetic tape. Program GLIP is used to convert all measurement values (counts/second, millivolts, etc.) to physical property parameters (apparent density in g/cc, electrical resistivity in ohm-meters, etc.) by use of calibration and correction formulas. The program also computes all synthetic logs including elastic moduli, Poisson's ratio, RQD, temperature gradient, borehole inclination and fracture orientation. Program options make it possible to obtain printer plots of all computed logs, and/or to store all program output results on magnetic tape or disk for Calcomp X-Y plotting by the third program, LPLOT, at a later time. A flow chart of program GLIP is given in Figure 12.

The third program, LPLOT, reads the GLIP output data stored on magnetic tape or disk, and plots it on a 30-inch Calcomp X-Y plotter. Depth scales and depth intervals for plotting are selected by the user and submitted to the program on control cards. A flow chart of program LPLOT is given in Figure 13.

Representative final results obtained by use of the three computer programs are shown on the Calcomp plots of Figure 14 and Figure 15. Log parameter curves

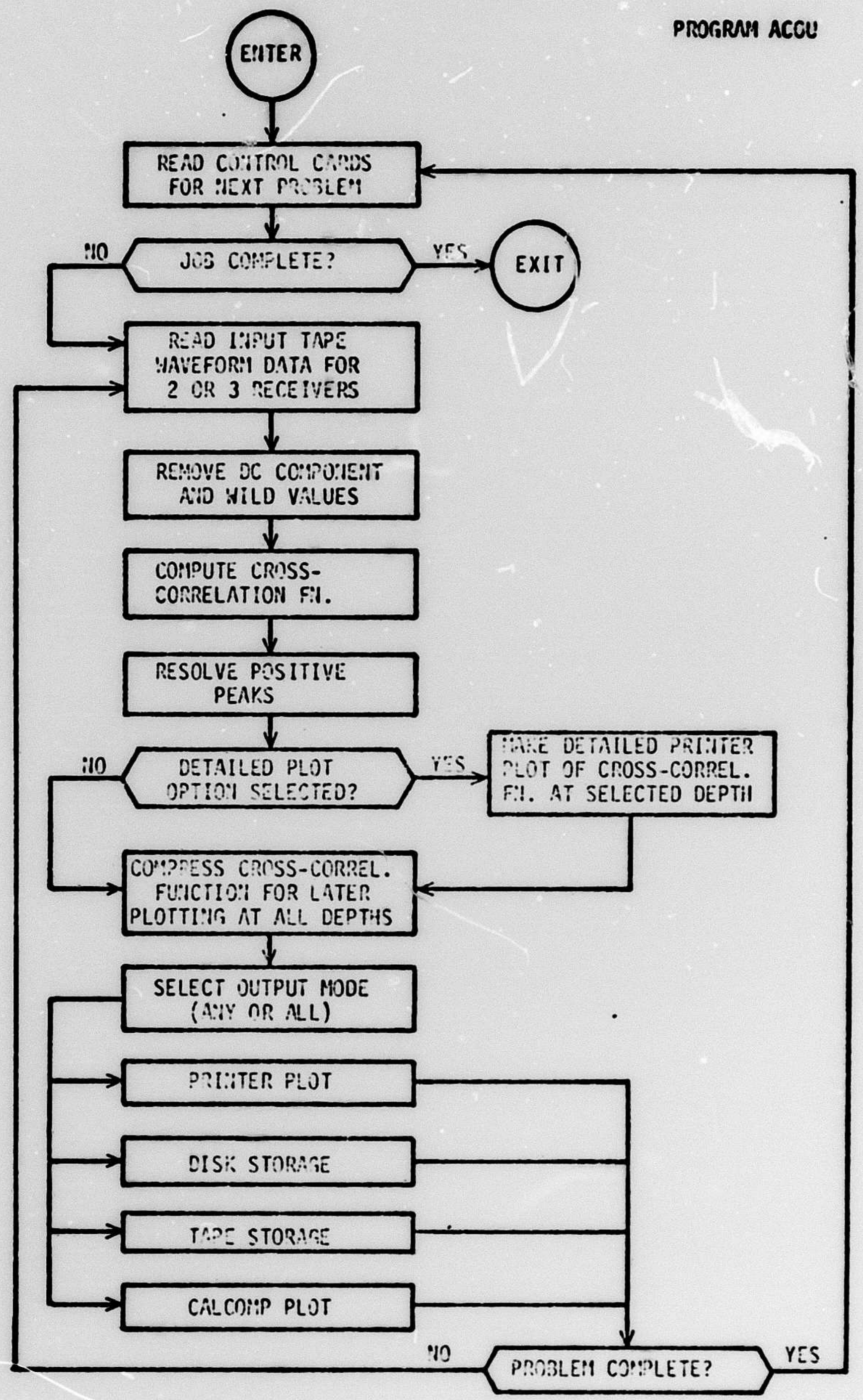

FIGURE 11. - Flow Chart of Computer Program ACOU for Analyzing Acoustic Logs.

PROGRAM GLIP

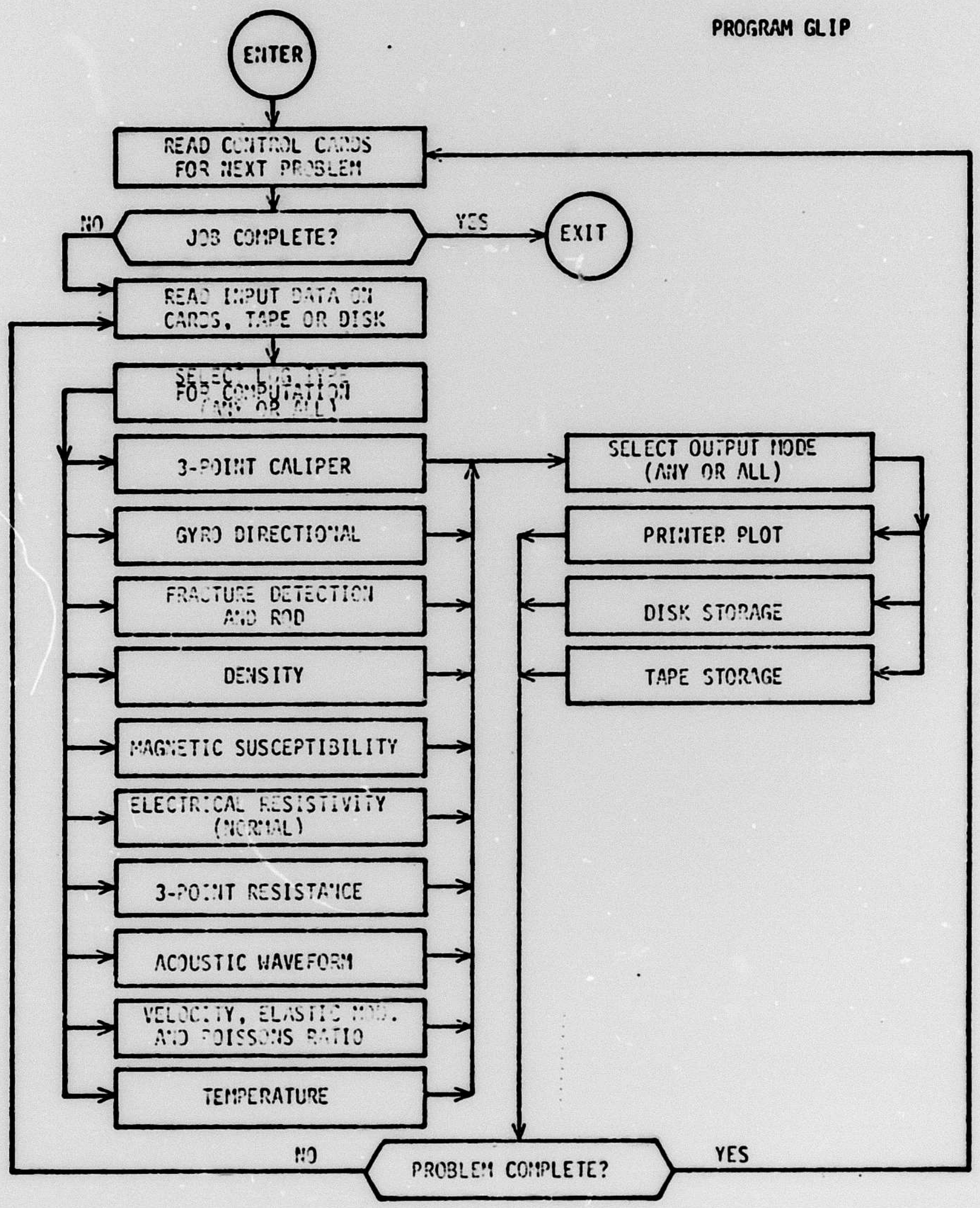

FIGURE 12. - Flow Chart of Computer Program GLIP for Analyzing Geophysical Logs.

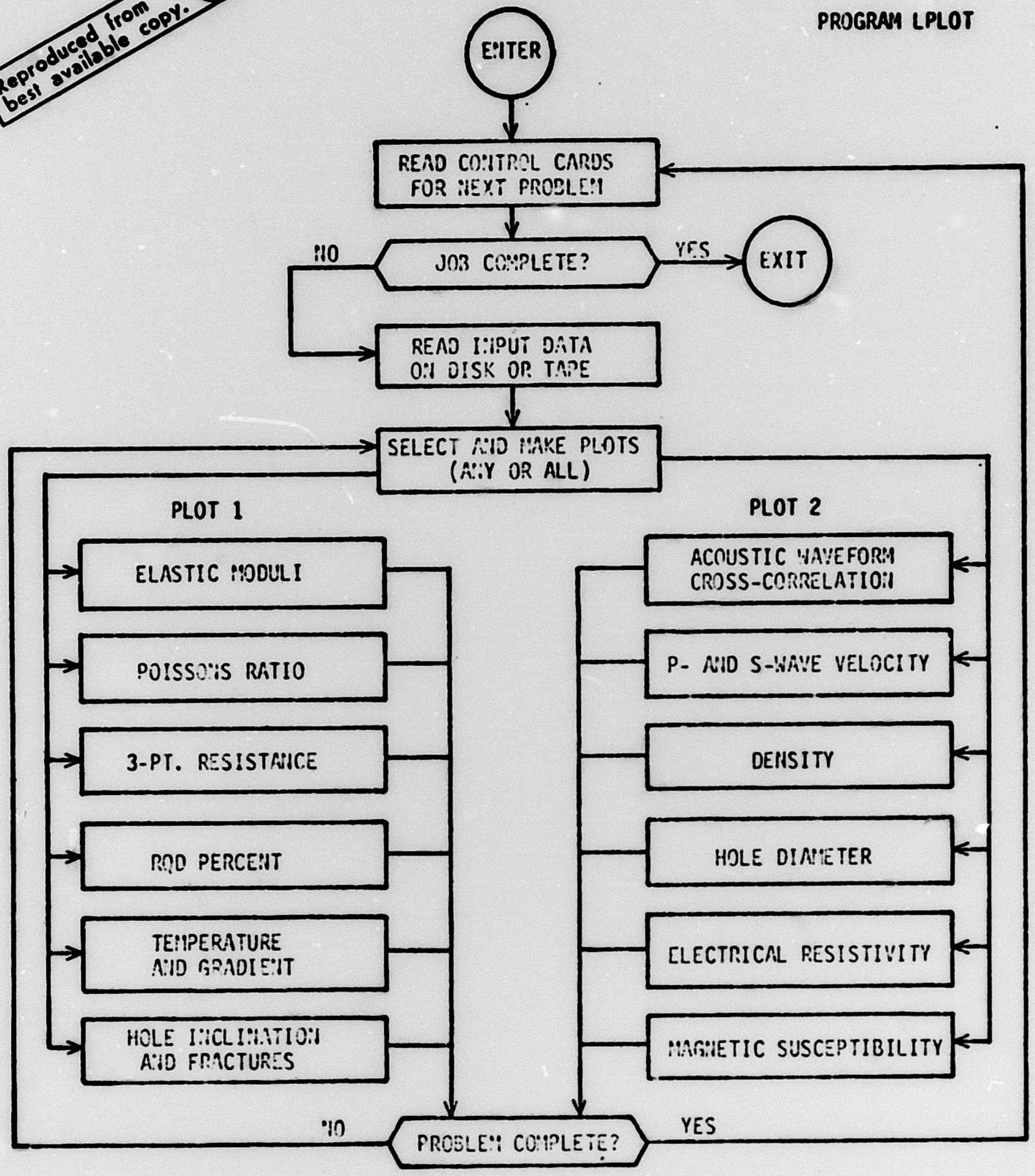

FIGURE 13. - Flow Chart of Computer Program LPLOT for Making Calcomp Plots.

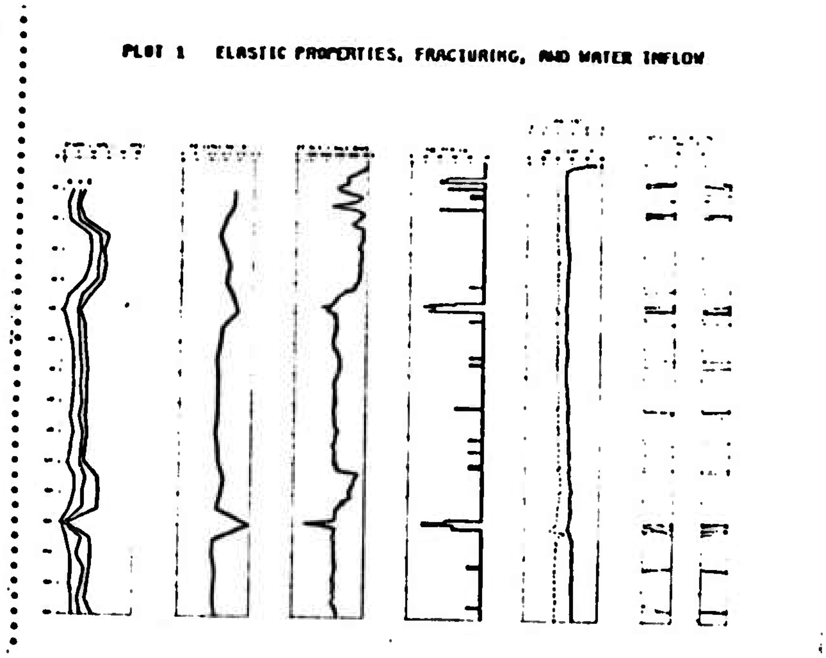

FIGURE 14. - Calcomp Plot 1 Showing Computed Logs for Interpreting Elastic Properties, Fracturing and Water Inflow. Left to Right: Dynamic Elastic Moduli, Poisson's Ratio, 3-Point Resistance, RQD, Temperature and Hole Inclination and Fractures.

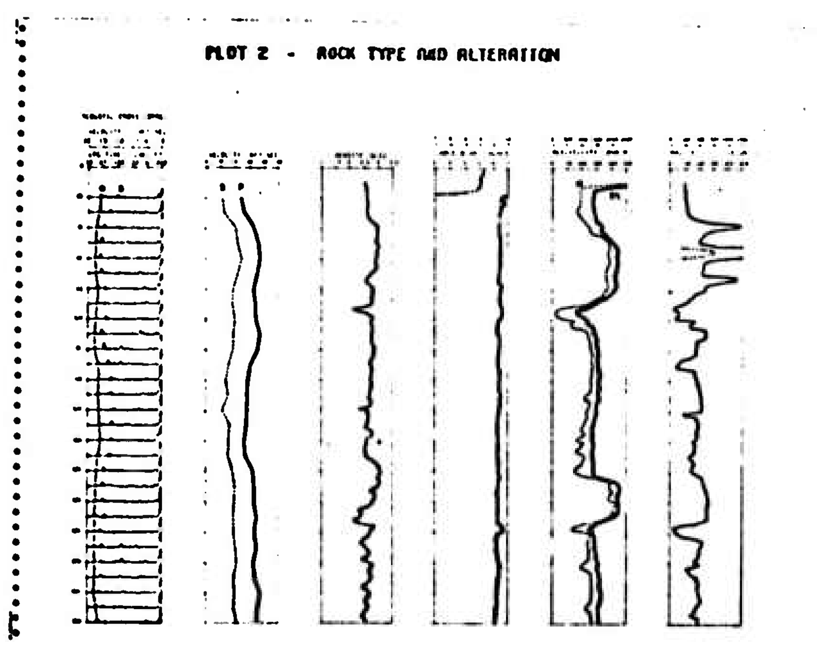

FIGURE 15. - Calcomp Plot 2 Showing Computed Logs for Interpreting Rock Type and Alteration. Left to Right: Acoustic Waveform Cross-Correlation, P- and S-Wave Velocity, Bulk Density, Hole Diameter, Electrical Resistivity, and Magnetic Susceptibility.

in these illustrations have been over-drafted for clarity and emphasis in the photo-reduced illustration. Note that the fracture zone near the bottom of the hole is indicated by anomalous values on all of the logs in Plot 1 of Figure 14. Differences in rock type are clearly shown by the electrical resistivity log and the magnetic susceptibility log, and also, though less distinctly, by the density and velocity logs in Plot 2 of Figure 15.

As new geophysical logging techniques are developed by the Bureau of Mines in future research programs, new methods of data interpretation and display will also be developed and made available to the public through future reports. Anyone interested in receiving up to date information on our progress may contact the authors at the address given on page 1 of this report.

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